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The $Z \to \overline{b}b$ decay asymmetry and flavor changing neutral currents [1]

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Abstract

The measured value of A_b, the $Z\overline{b}b$ asymmetry parameter, disagrees with the Standard Model at 99% confidence level. If genuine the discrepancy could indicate new interactions unique to third generation quarks, implying enhanced Z penguin amplitudes. Enhanced rates are predicted for rare K and B decays, such as $K^+ \to \pi^+\overline{\nu}\nu$, $K_L \to \pi^0\overline{\nu}\nu$, $B \to X_s\overline{\nu}\nu$, and $B_s \to \overline{\mu}\mu$. Measurements of ϵ'/ϵ then imply QCD penguin amplitudes must also be similarly enhanced. The Higgs sector of an $SU(2)_L \times SU(2)_R$ gauge theory has some of the features needed to explain these phenomena and would also imply right-handed penguin amplitudes.

Note: The revision includes predictions for additional K and B decays.

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Introduction Each successive update of the precision electroweak data tends to reinforce the already spectacular agreement with the Standard Model (SM). An exception emerged in the Summer 1998 update, when new data from SLC on the b quark front-back, left-right polarization asymmetry, A^b_{FBLR}, reinforced a possible discrepancy previously implicit in the LEP front-back asymmetry measurement, A^b_{FB}. Combined the two measurements implied a value for the b asymmetry parameter A_b three standard deviations (σ) below the SM value. The discrepancy continues today, though diminished to 2.6σ in the Spring 1999 data[1], implying inconsistency with the SM at 99% confidence level (CL).

The convergence of the SLC and LEP determinations of A_b at a value in conflict with the SM could resolve the longstanding disagreement between the SLC and LEP measurements of the effective weak interaction mixing angle, $\sin^2\theta^\ell_W$, a critical parameter that currently provides the most sensitive probe of the SM Higgs boson mass. If A_b is affected by new physics then A^b_{FB} must be removed from the SM fit of $\sin^2\theta^\ell_W$, leaving the remaining measurements in good agreement. This possibility is also consistent with theoretical prejudice that the third generation is a likely venue for the emergence of new physics.

On the other hand the discrepancy could have an experimental origin. The now resolved R_b anomaly illustrates the difficulties, which may be even greater for A_b and A^b_{FB}. Or it could be a statistical fluctuation. Unfortunately the study of Z decays is nearing its end. When the dust settles we may still be left wondering about the significance of the discrepancy.

The purpose of this paper is to observe that there is another arena in which the A_b anomaly can be studied. If it is a genuine sign of new physics unique to (or dominant in) the third generation, new phenomena must emerge in flavor-changing neutral current (FCNC) processes. Then if the underlying physics has a mass scale much greater than m_W and m_t, Z penguin amplitudes are enhanced by about a factor two. The cleanest tests are rare K and B decays, such as $K^+ \to \pi^+\overline{\nu}\nu$, $K_L \to \pi^0\overline{\nu}\nu$, $B \to X_s\overline{\nu}\nu$, and $B_s \to \overline{\mu}\mu$. For instance $K^+ \to \pi^+\overline{\nu}\nu$ is enhanced by a factor 1.9 relative to the SM. A single event has been observed, with nominal central value from 1.8 to 2.7 times the SM prediction quoted below.[2]

The A_b anomaly could arise from new physics in the form of radiative cor-

rections or $Z - Z'$ or $b - Q$ mixing. In the first case, but not in the latter two, there would generically also be enhanced gluon (and photon) penguin amplitudes. This possibility is favored by the recent measurements of ϵ'/ϵ, since the Z penguin enhancement by itself exacerbates the existing disagreement with the SM, although the theoretical uncertainties are considerable. The gluon penguin enhancement cannot be deduced in a model independent way from the A_b anomaly but can be estimated from ϵ'/ϵ. Enhanced Z and gluon penguins can be tested in B meson decays and elsewhere. They would have a big impact on studies of the CKM matrix and CP violation.

Fits of the b quark couplings In the SM the b quark asymmetry parameter is $A_b = 0.935$ with negligible uncertainty. In terms of the left- and right-handed $Z\overline{b}b$ couplings $g_{bL,R}$ it is

$$A_b = \frac{g_{bL}^2 - g_{bR}^2}{g_{bL}^2 + g_{bR}^2}. \tag{1}$$

It is measured directly by the front-back left-right asymmetry, $A_b = A_{FBLR}^b = 0.898(29)$[1] and also by the front-back asymmetry using $A_b = 4A_{FB}^b/3A_\ell$ where A_ℓ ($\ell = \mathrm{e}, \mu, \tau$) is the lepton asymmetry parameter defined as in eq. (1) with $b \to \ell$. Using $A_{FB}^b = 0.0991(20)$ from LEP and $A_\ell = 0.1489(17)$ from the combined leptonic measurements at SLC and LEP, we find $A_b = 0.887(21)$. The two determinations together imply $A_b = 0.891(17)$.

I have performed several fits to the five quantities that most significantly constrain g_{bL} and g_{bR}. In addition to A_b and the ratio of partial widths, $R_b = \Gamma_b/\Gamma_h$, they are the total Z width Γ_Z, the peak hadronic cross section σ_h, and the hadron-lepton ratio $R_\ell = \Gamma_h/\Gamma_\ell$. A brief summary is presented here; details will be given elsewhere.[3]

The SM fit assumes $\sin^2\theta_W^\ell = 0.23128(22)$ as follows from A_ℓ. It has chi-squared per degree of freedom $\chi^2/dof = 10.4/5$ with confidence level $CL = 6.5\%$. In fit 1 g_{bL} and g_{bR} are allowed to vary while all other $Z\overline{q}q$ couplings are held at their SM values, yielding $\chi^2/dof = 3.0/3$ and $CL = 39\%$. In fit 2 only g_{bR} is allowed to vary; the result is $\chi^2/dof = 7.8/4$ with $CL = 10\%$, little better than the SM fit. In fit 3 the couplings of the b, d and s quarks are varied equally, $\Delta g_{bL,R} = \Delta g_{dL,R} = \Delta g_{sL,R}$; with a result nearly as good as fit 1. Other fits considered resulted in poorer CL's than the SM.

We conclude that positive shifts are preferred for both g_{bL} and g_{bR}, either

for the b quark alone as in fit 1 or for b, d and s equally as in fit 3. The need to shift both left and right couplings is clear: $\delta A_b \simeq -0.05$ requires positive shifts in g_{bR} and/or g_{bL} (remember that $g_{bL} < 0$) while $g_{bL}^2 + g_{bR}^2$ is tightly constrained by the other measurements, forcing $\delta g_{bR}^2 \simeq -\delta g_{bL}^2$. Fit 3 seems unnatural in that s, d couplings are varied while u, c couplings are not, an issue finessed in fit 1 which presumeably reflects physics unique to the third generation quarks, perhaps due to the large value of the top quark mass. The 32% and 5% contours from fit 1 are shown in figure 1, with the SM values, $g_{bL}, g_{bR} = -0.4197, +0.0771$, and the fit central values, $g_{bL}, g_{bR} = -0.4154, +0.0997$.

The Z penguin enhancement We now focus on fit 1 and the FCNC effects it implies. Physics from higher mass scales will couple to the $SU(2)_L$ quark eigenstates, so a nonuniversal $Z\overline{b}_L b_L$ coupling, δg_{bL}, has its origin in a nonuniversal $Z\overline{b}'_L b'_L$ amplitude where b'_L is the weak eigenstate, $b'_L = V_{tb} b_L + V_{ts} s_L + V_{td} d_L$. As a result $Z\overline{b}s$, $Z\overline{b}d$, , and $Z\overline{s}d$ interactions are induced.

The very same phenomenon occurs in the SM where the leading correction to the $Z\overline{b}b$ vertex arises from t quark loop diagrams. For $m_t \to \infty$ the leading correction is[4]

$$\delta g_{bL}^{\rm SM} = \frac{\alpha_W(m_t)}{16\pi}\frac{m_t^2}{m_W^2} \tag{2}$$

where $\alpha_W = \alpha/\sin^2\theta_W^\ell$. For $m_t = 174.3$ GeV this is $\delta g_{bL}^{\rm SM} \sim 0.0031$. A more complete estimate based on the complete one loop result[5] and with the pole mass m_t replaced by the running $\overline{MS}$ mass, $\overline{m}_t(m_t) \simeq m_t - 8$ GeV,[6] yields a similar result, $\delta g_{bL}^{\rm SM} = 0.0032$, resulting in $g_{bL} = -0.4197$. In fit 1 g_{bL} is shifted by an additional amount, $\delta g_{bL}^{\rm A_b} = 0.0043$. These are large shifts: e.g., $\delta g_{bL}^{\rm SM}$ corresponds to a 3σ effect in R_b.

The same Feynman diagrams responsible for the leading $Z\overline{b}b$ vertex correction also generate the SM Z penguin amplitude and in the limit $m_t \to \infty$ they are identical. Rewriting the one loop Z penguin vertex for $\overline{s}d$ transistions as an effective $\delta g_{\overline{s}dL}^{\rm SM}$ coupling normalized like g_{bL}, we have (see eq. (2.18) of [6])

$$\delta g_{\overline{s}dL}^{\rm SM} = \lambda_t \frac{\alpha_W}{2\pi} C_0(x_t) \tag{3}$$

where $\lambda_t = V_{ts}^* V_{td}$, $x_t = m_t^2/m_W^2$, and C_0 is

$$C_0(x) = \frac{x}{8}\left(\frac{x-6}{x-1} + \frac{3x+2}{(x-1)^2}\ln(x)\right) \tag{4}$$

Taking $m_t \gg m_W$ and comparing with eq. (2) we have

$$\delta g^{\rm SM}_{\overline{s}dL} = \lambda_t \delta g^{\rm SM}_{bL}. \tag{5}$$

Eq. (5) shows that if m_t were much larger than any other relevant scale we could smoothly extrapolate the on-shell $Z\overline{b}b$ vertex correction to the related $Z\overline{q}'q$ penguin vertex. The same is true of any new physics at a scale $m_X \gg m_W, m_t$, whether it affects the $Z\overline{b}b$ vertex by radiative corrections or by $Z - Z'$ or $b - Q$ mixing. Therefore if the A_b anomaly arises from physics at a very high scale, the additional contribution to the $\overline{s}d$ Z penguin amplitude is

$$\delta g^{\rm A_b}_{\overline{s}dL} = \lambda_t \delta g^{\rm A_b}_{bL}. \tag{6}$$

With $\delta g^{\rm A_b}_{bL}$ from fit 1, the contribution of $\delta g^{\rm A_b}_{\overline{s}dL}$ is equal in sign and magnitude to the SM Z penguin, resulting in a factor two enhancement in amplitude.

Rare K and B decays The enhancement of the Z penguin implies increased rates for the rare K decays $K_L \to \pi^0\overline{\nu}\nu$ and $K^+ \to \pi^+\overline{\nu}\nu$, and the rare B decays $B \to X_s\overline{\nu}\nu$, and $B_s \to \overline{\mu}\mu$. The predicted enhancement is consistent with the bound on the real part of the Z penguin amplitude obtained in [7] from $K_L \to \overline{\mu}\mu$.

Predictions for the rare K decays are obtained following [7] (with parametric updates from [8]), since Z_{ds} defined in [7, 8] is $Z_{ds} = \lambda_t(C_0(x_t) + C_b)$ where

$$C_b = \frac{2\pi}{\alpha_W}\delta g^{A_b}_{bL} \tag{7}$$

with $\alpha_W = \alpha/\sin^2\theta^\ell_W$. The results are

$$\mathrm{BR}(K_L \to \pi^0\overline{\nu}\nu) = 6.78 \cdot 10^{-4}(\mathrm{Im}\lambda_t)^2 \left|X_0(x_t) + C_b\right|^2 \tag{8}$$

and

$$\mathrm{BR}(K^+ \to \pi^+\overline{\nu}\nu) = 1.55 \cdot 10^{-4} \left|\lambda_t \left(X_0(x_t) + C_b\right) + \Delta_c\right|^2 \tag{9}$$

where Δ_c is a nonnegligible charm quark contribution and $X_0 = C_0 - 4B_0$ is a combination of the SM t quark Z penguin and box amplitudes. The SM box amplitude, $\sim B_0$, is essential for gauge invariance and is numerically important in 't Hooft-Feynman gauge in which we work. In the limit $m_t \gg m_W$ it is suppressed by m_W^2/m_t^2 relative to the penguin because of its softer UV behavior.

We assume for the new physics underlying the A_b anomaly that the penguin amplitude dominates over the box, as expected for instance in models with "hard GIM suppression."[8]

Similarly, following the parameterization in [6], the B decay rates are

$$\mathrm{BR}(B \to X_s \overline{\nu}\nu) = 1.52 \cdot 10^{-5} \left|\frac{V_{ts}}{V_{cb}}\right|^2 |X_0(x_t) + C_b|^2 \tag{10}$$

and

$$\mathrm{BR}(B_s \to \overline{\mu}\mu) = 3.4 \cdot 10^{-9} \, |Y_0(x_t) + C_b|^2 \tag{11}$$

where $Y_0 = C_0 - B_0$. $\mathrm{BR}(B \to X_d \overline{\nu}\nu)$ can be obtained by substituting V_{td} for V_{ts} in eq. (10), and $\mathrm{BR}(B_d \to \overline{\mu}\mu)$ can be obtained from eq. (11) using

$$\frac{\mathrm{BR}(B_d \to \overline{\mu}\mu)}{\mathrm{BR}(B_s \to \overline{\mu}\mu)} = \frac{\tau(B_d)}{\tau(B_s)} \frac{m_{B_d}}{m_{B_s}} \frac{F^2_{B_d}}{F^2_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2}. \tag{12}$$

The results are displayed in table 1. For the A_b anomaly the branching ratios are enhanced by factors between $\simeq 2$ and $\simeq 3$. The SM error estimates are taken from [6, 7, 8]. For the A_b anomaly two errors are quoted: the first is the parametric and theoretical error that is common to the A_b anomaly and the SM, while the second reflects a ± 0.0014 uncertainty in $\delta g^{A_b}_{bL}$. The uncertainties of the ratios are dominated by the uncertainty in $\delta g^{A_b}_{bL}$ alone.

The ratios differ from unity by about 2.6σ, which is the significance of the A_b anomaly itself, whereas the predicted branching ratios differ less significantly because of the common parametric and theoretical error. The most significant difference is for $B \to X_s \overline{\nu}\nu$, which has the smallest parametric/theoretical error. Combining all errors in quadrature, the predicted SM and A_b anomaly branching ratios for $B \to X_s \overline{\nu}\nu$ differ by 2.3σ. For $K_L \to \pi^0 \overline{\nu}\nu$, $K^+ \to \pi^+ \overline{\nu}\nu$, and $B_s \to \overline{\mu}\mu$ the differences are 1.2σ, 1.0σ, and 1.6σ respectively. The precision of the K decay predictions improves as the CKM matrix is measured more precisely, while the $B_s \to \overline{\mu}\mu$ prediction depends on the decay constant F_{B_s}. If instead of [8] we take λ_t from the CKM fit of [10] the precision of the K decay predictions is improved.[3]

$\underline{\epsilon'/\epsilon}$ Theoretical estimates of ϵ'/ϵ suggest that the $\delta g^{A_b}_{\bar{s}dL}$ Z penguin enhancement is disfavored unless QCD penguins are also enhanced. From the approximate analytical formula in [7] we find $\epsilon'/\epsilon = +7.3 \cdot 10^{-4}$ for the SM and $\epsilon'/\epsilon = -0.2 \cdot$

10^{-4} with the $\delta g^{A_b}_{\bar{s}dL}$ Z penguin enhancement.[9] The most recent experimental average (with scaled error) is[11] $(\epsilon'/\epsilon)_{\rm Expt} = (21.2 \pm 4.6) \cdot 10^{-4}$.

Taking the theoretical estimates at face value, consistency requires that gluon penguins are also enhanced. If the principal gluon penguin term is enhanced by the same factor ($\simeq 2$) as the Z penguin, the result is $15 \cdot 10^{-4}$, while a factor 3 enhancement yields $29 \cdot 10^{-4}$.

However a large unquantifiable uncertainty hangs over all theoretical estimates of ϵ'/ϵ. Presently they depend sensitively on the strange quark running mass and the hadronic matrix elements $B_6^{\frac{1}{2}}$ and $B_8^{\frac{3}{2}}$, each estimated by non-perturbative methods not yet under rigorous control. Consequently we cannot conclude that the SM or the $\delta g^{A_b}_{\bar{s}dL}$ enhanced Z penguin are truly inconsistent with the data. The uncertainties will hopefully be resolved by more powerful lattice simulations. Until then conclusions based on (ϵ'/ϵ) must be regarded with caution.

Discussion The A_b anomaly could be caused by radiative corrections of new bosons and/or quarks, by $Z-Z'$ mixing, or by $b-Q$ mixing with heavy quarks Q in nonstandard $SU(2)_L$ representations. Generically radiative corrections would also affect gluon and photon penguin amplitudes, by model dependent amounts, while $Z - Z'$ and $b - Q$ mixing would only enhance the Z penguin. With the major caveat expressed above, ϵ'/ϵ appears to favor radiative corrections, since it could be explained if the gluon penguin is enhanced by a similar factor to the $\delta g^{A_b}_{\bar{s}dL}$ Z penguin enhancement.

The hypothesis that the A_b anomaly represents the effect of higher energy physics on third generation quarks can be falsified if the predicted Z penguin enhancements are absent. If they are present the hypothesis remains viable and the A_b anomaly provides key information beyond the FCNC studies. The large value of δg_{bR} and the condition $\delta(g^2_{bR} - g^2_{bL}) \gg |\delta(g^2_{bL} + g^2_{bR})|$ would then point to a radical departure from the SM with a sharply defined signature. For instance, the Higgs sector associated with a right-handed extension of the SM gauge sector could shift g_{bR} and g_{bL} with little effect on other precision measurements. Depending on the right-handed CKM matrix, there could also be observable right-handed FCNC effects.

The burgeoning program to study CP violation and the CKM matrix must

measure Z and gluon penguin amplitudes in order to fully achieve its goals — an enterprise characterized as controlling "penguin pollution." In the process we should learn if the FCNC effects implied by fit 1 occur or not. If they do "penguin pollution" would be transformed into a window on an unanticipated domain of new physics, of which the measurement of A_b would have provided the first glimpse.

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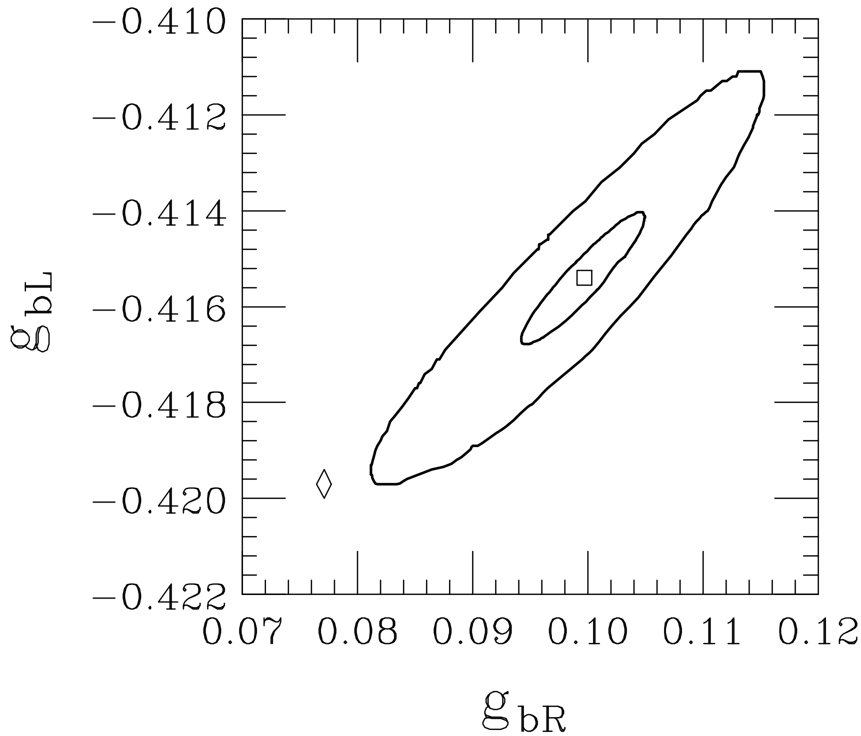

Figure 1. χ^2 contours for fit 1. The diamond is the SM prediction and the box is the best value from fit 1. The inner contour indicates $\chi^2 = 3.5$ corresponding to CL = 32% for 3 *dof*. The outer contour indicates $\chi^2 = 7.8$ corresponding to CL = 5% for 3 *dof*.

Table 1. Predicted branching ratios for the $\delta g_{\bar{s}dL}^{A_b}$ enhanced Z penguin amplitude and for the SM. The third line displays the ratio of the enhanced predictions to the SM.

	$K_L \to \pi^0 \overline{\nu}\nu$ 10^{-11}	$K^+ \to \pi^+ \overline{\nu}\nu$ 10^{-11}	$B \to X_s \overline{\nu}\nu$ 10^{-5}	$B_s \to \overline{\mu}\mu$ 10^{-9}
$\delta g_{\bar{s}dL}^{A_b}$	$6.6 \pm 2.4^{+1.6}_{-1.4}$	$14.6 \pm 5.7^{+2.7}_{-2.5}$	$7.8 \pm 0.9^{+1.9}_{-1.7}$	$10.7 \pm 3.7^{+3.4}_{-2.9}$
SM	2.8 ± 1.1	7.7 ± 3.0	3.3 ± 0.4	3.2 ± 1.1
Ratio	$2.3^{+0.6}_{-0.5}$	$1.9^{+0.4}_{-0.3}$	$2.3^{+0.6}_{-0.5}$	$3.3^{+1.1}_{-0.9}$